

"Synthesis of nanoparticles with a closed structure of metal chalcogenides having a lamellar crystallographic structure and uses thereof"

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The present invention relates to the synthesis of nanoparticles with a closed structure of metal chalcogenides having a lamellar crystallographic structure, of the general formula M_aX_b , in which M 10 represents a metal and X a chalcogen, a and b representing the respective proportions of metal and chalcogen.

Such chalcogenides, in particular the dichalcogenides 15 of transition metals (MX_2), are materials used industrially in the field of lubrication and catalysis (in particular for petroleum hydrodesulfurization).

With regard to dichalcogenides, these have a structure 20 which is hexagonal (for example 2H-MoS₂) and lamellar, i.e. composed of 001-oriented crystallographic planes which form a structure of MX_2 lamellae known as van der Waals lamellae.

An MX_2 lamella is composed of a plane of metal atoms (M) sandwiched between two planes of chalcogen atoms (X). Within the lamellae, the atomic bonds between M and X are covalent and thus strong. In contrast, the lamellae are joined together by weak atomic interactions (van 30 der Waals forces between the chalcogen planes), so permitting easy glide perpendicular to the (001) planes, which explains their ability to provide a lubricating action in the solid state.

The tribological properties of solid lubricants such as graphite and dichalcogenides MX_2 are of great industrial and technological interest with regard to reducing friction. They are used when liquid lubricants do not work or as additives to enhance the performance of 35

liquid lubricants. MoS₂, for example, is well known for its use in the space industry and in a certain number of dispersions in grease, lacquers and as additives in engine oils, in particular in the automotive industry.

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In an ultra-vacuum, coatings of pure, stoichiometric MoS₂, obtained by solid atomization, have an extremely low coefficient of friction, of the order of 10⁻³. In order to allow MoS₂ coatings to slip relative to one another, the crystallites are reoriented with their base planes (van der Waals planes) parallel to the direction of sliding.

10 Although these materials have remarkable anti-friction and slip properties with an extended service life when they are used under vacuum, these lubrication capabilities become poor in the presence of moisture and/or oxygen, so restricting the use thereof in the earth's atmosphere. MoS₂ powder has a very short life and a considerably higher coefficient of friction, greater than 0.1, when it is used in moist and/or oxygenated environments. In ambient atmosphere, i.e. with a relative humidity of 50%, the 2H polytype sheets have a tendency to stick to metallic parts due to the presence of pendant bonds, resulting in deterioration 20 and rapid oxidation.

25 The development of new, better quality and more effective lubricants is a challenge from both an economic and an environmental point of view.

30 It has recently been shown that MoS₂ and WS₂ nanoparticles in the form of inorganic fullerenes and nanotubes have tribological properties which are very much better than those of these materials in the form of conventional particles (hexagonal sheets of 2H structure) over a wide range of operating conditions

(concentration, load, load/speed ratio, temperature and pressure, etc.).

MoS₂ fullerenes have a low coefficient of friction close
5 to 0.04 both under lubrication conditions, as additives
in oils, and as coatings under ultra-vacuum conditions.
Since the fullerene structure has very few pendant
bonds, it provides great chemical stability even when
the fullerenes are in contact with ambient air and in
10 particular oxygen. Their round and hollow shape is
another favorable factor because it permits deformation
without breakage, due to a certain degree of resilience
in the structure, and thus better durability over time.

15 As indicated previously, because they have been
discovered only recently, the new forms of MX₂
(fullerenes and nanotubes) are not used industrially.
Only the conventional (2H) sheet shape, of various
dimensions (from 1 to several hundred microns), is
20 widely used in many fields and in different
presentations (powder, additives, coating, etc.).

Furthermore, only one method is currently available
which allows the synthesis of appreciable quantities of
25 pure inorganic fullerene or MX₂ nanotube phases. These
products (inorganic fullerenes) have only very recently
been introduced commercially and they are available in
quantities of the order of one gram, under the name
Nanolub™ from the startup company "Applied Materials".

30 The method used involves reacting nanoparticles of MO₃ =
(M = Mo, W) in sheet or needle form with gaseous
hydrogen sulfide or selenide (H₂S and H₂Se) at
temperatures in excess of 800°C. The reactor which has
35 been developed allows MO₃ nanoparticles to be introduced
continuously into the furnace, conveyed by an H₂/N₂
carrier gas. The carrier gas also has the function of
reducing the metal from oxidation state VI to oxidation

state IV. It is assumed that the mechanism underlying the formation of the hollow MX_2 particles involves the formation of an intermediate amorphous MX_3 phase.

- 5 Other methods are under development, but at present remain at the experimental, laboratory stage.

Application WO 00/66485, for example, relates to the synthesis of transition metal chalcogenide nanotubes 10 starting from a transition metal or a compound containing said transition metal, for example an oxide, water vapor and a gaseous chalcogen hydride or alternatively molecular hydrogen and a vapor-phase chalcogen.

15 US patent 6,217,843 describes a method for the preparation of, on the one hand, metal oxide nanoparticles containing inserted metal particles and, on the other hand, metal-intercalated and/or metal-encaged inorganic fullerene-like structures. These 20 structures are metal chalcogenides obtained from the nanoparticles in question. This method involves heating a group I metal in water vapor or electron-beam evaporating a group I metal in question with water or any other appropriate solvent in the presence of a 25 group II metal salt. The method then involves either recovering the group I metal oxide doped with group II metal or proceeding to subsequent sulfidization.

30 Patent application WO 0166676 relates to applications of metal chalcogenide fullerenes and the only compound synthesis it mentions is the reaction of a chalcogen hydride on a transition metal oxide.

35 Patent application WO 0104382 concerns inorganic fullerene-like nanoparticles of metal chalcogenides comprising one or more layers of desired sizes and

shapes. These nanoparticles are produced by sonoelectrochemical liquid-phase synthesis.

Patent application WO 9744278 relates to a method of preparing inorganic fullerene-like nanoparticles of a metal, for example transition metal, chalcogenide having the desired size and shape, at high yields and in macroscopic quantities. The method comprises the steps of dispersing solid particles of at least one nonvolatile metal material having the preselected size and shape, heating the solid particles of the nonvolatile metal material in a reducing gaseous atmosphere containing at least one chalcogen for a time and at a temperature sufficient to allow the metal material precursor and the chalcogen to react and form at least one layer of metal chalcogenide covering the surface of the solid particles to form fullerene-like particles, and recovering the thus obtained macroscopic quantities of the metal chalcogenide.

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Generally, the major drawbacks of the techniques described in the prior art are associated with the use of the highly toxic gases H₂S and H₂Se and with the small quantities produced, of the order of a few grams per hour. Furthermore, synthesis of the inorganic fullerenes of MoS₂ and WS₂ *inter alia* and of all transition metal chalcogenide nanoparticles starting from a solid/gas chemical reaction does not allow the size and shape of the nanoparticles, and in particular of the fullerenes, to be controlled, so affecting the tribological performance of these materials, especially under conditions of elevated load and sliding speed.

The inventors have developed, and this forms the subject matter of the present invention, a method for the synthesis of nanoparticles of metal chalcogenides M_aX_b which overcomes these drawbacks and in particular the problems of toxicity of the compounds required for

this synthesis, while simultaneously enabling larger-scale production.

The inventors observed that these various problems
5 could be resolved by implementing a synthesis method
based on the pyrolysis of precursors of the materials
used.

This technique is mentioned in various documents.

10 Accordingly, US patent 5,427,763 reports the synthesis
of vanadium dioxide in powder form by spray pyrolysis.
This method, however, gives rise to micron-sized powder
particles.

15 Application WO 01/32799 relates to dispersions of
nanoscale particles, in particular of carbon, of metal,
of oxides, of carbides or of sulfides of
metal/silicone. The technique used in this case is
20 laser pyrolysis.

EP application 0 285 339 describes the use of the spray
pyrolysis technique for obtaining dense metal oxide or
metal sulfide particles.

25 The work carried out by the inventors in this field
revealed that the spray pyrolysis technique could be
used in order to obtain metal derivatives having
structures differing from those intended in the above
30 prior art documents.

The invention therefore relates to the use of a spray
pyrolysis method in the synthesis of nanoparticles of a
particular structure.

35 It also relates to the uses of the nanoparticles
obtained.

A further object of the invention is to provide nanoparticles of a new morphology.

The invention therefore relates to a spray pyrolysis method characterized in that it is applied to the synthesis of nanoparticles with a closed structure of metal chalcogenides having a lamellar crystallographic structure, and comprises the pyrolysis of a liquid aerosol obtained from a solution of at least one precursor of a metal (M) and of a chalcogen (X), or of at least one precursor of said metal (M) and of at least one precursor of said chalcogen (X), dissolved in a solvent, said solution being atomized into fine droplets in suspension in a carrier gas.

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More particularly, the invention relates to the use of a pyrolysis method in the synthesis of said nanoparticles, said method comprising the following steps:

- 20 - formation of a solution of said at least one precursor of a metal and of a chalcogen, or of said at least one precursor of said metal and of said at least one precursor of said chalcogen in a solvent,
- atomization of said solution in liquid aerosol form
- 25 by a nebulizer, in particular of the pneumatic or ultrasonic type, through which the carrier gas is flowing,
- injection of the aerosol into a heated furnace to evaporate the solvent and to react and/or break down
- 30 said precursor(s) of the metal and of the chalcogen so as to form the nanoparticles,
- transport by the carrier gas of the nanoparticles to the furnace outlet, and
- recovery of the nanoparticles at the furnace outlet.

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Advantageously, said precursor of the metal and of the chalcogen contains both the metal and the chalcogen.

Such a precursor is in particular of the formula $(A)_cM(X)_d$ in which A is a cation such as K^+ , Na^+ or NH_4^+ , M is a metal and X a chalcogen, c and d respectively representing the number of cations and chalcogens.

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In one embodiment of the invention, said metal is a transition metal. Ti, Zr, Hf, V, Nb, Mo, W, Re, Ta, Co, Ni, Pt, Pd, Cr and Ru may be mentioned.

10 In another embodiment of the invention, said metal is a metal from group III of the Periodic Table of Elements, such as Ga or In.

15 In still another embodiment, said metal is a metal from group IV of the Periodic Table of Elements. It is, for example, Sn, Pb or Ge.

In still another embodiment, said metal is a metal from group V of the Periodic Table of Elements, such as Bi.

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The chalcogen is selected from among oxygen, sulfur, selenium and tellurium.

25 In particular, at least one of the precursors of the transition metal and of said chalcogen is a tetrathiometallate or a tetraselenometallate.

30 The metal of the tetrathiometallate or tetraselenometallate is advantageously selected from molybdenum and tungsten.

Said carrier gas is preferably an inert gas, such as nitrogen and argon, and/or hydrogen.

35 Said solvent is advantageously a polar solvent.

Still more advantageously, said solvent is selected from water and ethanol, or a mixture thereof.

The spray pyrolysis method as used according to the invention for the synthesis of said nanoparticles comprises in a first phase the atomization, in liquid aerosol form, that is to say in very fine droplets in suspension in a gas, of a solution containing one or more dissolved precursors of the metal and the chalcogen, using a nebulizer through which an inert gas (argon or nitrogen) is flowing. The resultant liquid aerosol is then injected into a furnace adjusted to an elevated temperature (typically of several hundred degrees), so bringing about in the droplets, on the one hand, evaporation of the solvent and, on the other hand, the reaction or the decomposition of the precursors to form MX_2 fullerenes or nanotubes. The latter are transported by the inert gas and finally collected at the furnace outlet.

The pyrolysis method used is based on the pyrolysis of a liquid aerosol at elevated temperature. A solution of reaction precursors is atomized with the assistance of an inert gas into micron-scale droplets which are in suspension in the gas (liquid aerosol) and each of which contains a certain quantity of dissolved precursors. This liquid aerosol is injected into a furnace at elevated temperature in which the droplets are converted into particles by direct pyrolysis, so forming a solid aerosol, that is to say particles in suspension in a gas. The solid aerosol is transported by the carrier gas and collected in powder form on a filter at the furnace outlet, or collected by bubbling into a solution which will then be centrifuged.

Numerous physical and chemical processes may occur while the droplets, then the particles, are suspended in the gas phase. These include evaporation of the solvent from the droplets, the onset of crystallization of the solute in the droplet at the solid/liquid

interface, reaction or decomposition of the precursors in the particle, diffusion processes in the particle which may give rise *inter alia* to changes in morphology, the evaporation of volatile species such as 5 metal oxides, the condensation of particles on the furnace walls, the formation of new particles by coagulation of the initial particles.

Generally, operating conditions, in particular with 10 regard to the size of the nanoparticles and/or the temperature and/or the residence time in the furnace, are adjusted so as to optimize the obtainment of closed structures as defined above. Implementation of the above arrangements, alone or in combination, gives rise 15 to inorganic fullerene-like nanoparticles, nanotubes or nanoboxes.

Said nanoboxes are novel products and consequently also fall within the scope of the invention. They are 20 closed, generally hollow right parallelepipeds and rectangles, namely of essentially rectangular cross-section.

Such nanoboxes, and in general the nanoparticles obtained, are of great interest in the production of 25 various industrial products, such as catalysts, lubricants, in the medical field, or as intercalation agents, for example for hydrogen storage.

30 The invention will be better understood on reading the detailed description given below by way of example and by reference to Figures 1 and 2, which show fullerenes, and to Figures 3 and 4 which respectively show nanoboxes in profile viewed from the front.

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A solution of ammonium tetrathiometallate or of ammonium tetraselenometallate $MX_4(NH_4)_2$ with M = molybdenum (Mo) or tungsten W at oxidation state VI; X

= sulfur (S) or selenium (Se), at a concentration of 4×10^{-4} M, is atomized with the assistance of a commercial nebulizer and an inert gas (Ar or N₂). A liquid aerosol made up of micron-scale droplets is
5 formed in this manner and transported through a tubular furnace, heated to between 600 and 1050°C, by the inert gas of the liquid aerosol which thus acts as carrier gas. The solution may be prepared from deionized water or an alcohol of the ethanol type for example.

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The advantage of using an alcoholic solvent arises from its low surface tension. Its viscosity facilitates the formation of very fine droplets, while its low boiling point enables easy evaporation. A pyrolytic
15 decomposition/reaction of the solution containing the precursor MX₄(NH₄)₂ occurs at elevated temperature.

The atomizer is a glass "spray head" for chromatography as sold by Bioblock Scientific. The optimum pressure
20 for the gas flowing in the atomizer is from 1.2 to 1.4 bar. The Thermolyne-brand tubular furnace can reach a temperature of 1200°C in 10°C steps. Various solvents such as water, ethanol, methanol or propanol were used, in which the tetrathiomolybdate (NH₄)₂MoS₄ or
25 tetrathiottungstate (NH₄)₂WS₄ salt (Aldrich) was dissolved.

Spherical fullerenes of MoS₂ were obtained by using the solvent ethanol when atomization is performed at 750
30 and 900°C.

Spherical particles of 200 nm in diameter are observed by SEM. They are granular in appearance. These same particles are hollow when observed by HRTEM. They are
35 formed of MoS₂ lamellae (van der Waals planes) closed on themselves. When the solvent used is distilled water atomized at 750°C, the particles look as if they are

formed from an assembly of spherical fullerenes from a few nm to several tens of nm in diameter.

When atomization is performed at higher temperature,
5 for example at 1050°C, the MoS₂ fullerenes are of larger size with a diameter of approximately 100 nm.

By way of illustration, figures 1 and 2 show fullerenes synthesized at 900°C starting from an ethanolic (figure
10 1) and aqueous (figure 2) solution of (NH₄)₂MoS₄, observed by high resolution transmission electron microscopy (HRTEM).

In the case of WS₂ formed from (NH₄)₂WS₄ dissolved in
15 ethanol atomized at 750 and 900°C, the SEM images show the formation of parallelepipedal particles and, if applicable, of spherical particles.

Examination by HRTEM reveals that these particles, as
20 shown in figures 3 and 4, are completely enclosed by well-aligned lamellae of WS₂. They contain curved lamellae of WS₂.

The present invention exhibits the advantage of making
25 it possible to manufacture a wide variety of materials in an advantageous manner, and at low cost, given the small number of operations to be carried out. The method of the invention makes it possible to obtain particles of well-defined dimensions by controlling the
30 size of the droplets generated by the atomizer and also to form dense or porous particles by controlling the evaporation dynamics of the droplets.

The experimental conditions of the method according to
35 the invention thus provide control of the size, the morphology and the degree of crystallinity of the nanoparticles formed and thus of their physical,

mechanical, optical, electronic and catalytic properties.